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Research on the Principles and Development History of Geographic Cartography

Lijiao Jin

Xi'an International Studies University, Xi'an, China

Abstract

This paper systematically reviews the principle system of geographic cartography, covering core elements such as projection transformation, scale, symbol systems, and color application. Through a historical analysis, it reveals the technological evolution trajectory from prehistoric rock paintings to modern digital maps, with a particular focus on the groundbreaking developments in cartographic techniques during the Ming and Qing dynasties. The study points out that geographic cartography has shifted from traditional empirical accumulation towards digitalization and intelligence, reflecting the continuous deepening of humanity's ability to perceive spatial information. Currently, geographic cartography is facing challenges such as data standardization and product diversification. In the future, it is necessary to strengthen interdisciplinary integration to meet complex spatial analysis demands.

Keywords

Geographic Cartography, Cartographic Principles, Technological Evolution, Ming and Qing Cartography, Digital Cartography.

1. Introduction

As a core means of visualizing and transmitting spatial information, geographic cartography has run through the entire history of human civilization [1]. From the simple markings of hunting routes on Neolithic rock paintings to the world maps of ancient Babylon and the agricultural field surveys in ancient Egypt, maps initially represented humanity's primitive attempts to perceive and record their living spaces. Cartography at this stage was mostly symbolic and mythological in nature. It was not until the ancient Greco-Roman period that cartography began to take on a scientific hue, with figures like Ptolemy proposing theories of latitude and longitude and map projections, and Pei Xiu of the Western Jin Dynasty in China summarizing the "Six Principles of Cartography." These developments laid the foundation for the two major traditions of cartography in the East and West, emphasizing mathematical foundations and a spirit of empirical measurement [2].

During the Ming and Qing dynasties, traditional Chinese cartography reached its peak through the integration with Western techniques. The *Complete Map of the Imperial Territory*, compiled under the auspices of Emperor Kangxi, was a landmark achievement [3]. It was the first large-scale application of modern surveying and mapping techniques based on astronomical observations and triangulation methods. Its coverage, measurement accuracy, and scientific systematicity represented the highest level of world cartography before the Industrial Revolution. It was hailed as "the best map in Asia at that time," profoundly reflecting the qualitative leap in humanity's global spatial cognition through the fusion of Eastern and Western knowledge. Meanwhile, the Age of Discovery in the West gave rise to the Mercator projection, which solved the critical problem of maintaining a constant course during navigation. The large-scale national topographic mapping based on triangulation in the 18th

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and 19th centuries formally established the precise and standardized paradigm of modern cartography [4].

The truly revolutionary transformation occurred in the mid-20th century. The introduction of computer technology propelled cartography from a labor-intensive manual craft into a new era of automation and digitalization. This was not merely a replacement of drawing tools but also triggered a profound paradigm shift-the emergence of Geographic Information Systems (GIS). The core of GIS lies in associating spatial locations with attribute information, enabling the overlay, management, and complex spatial analysis of map layers. It elevated cartography from an expressive art to a powerful spatial analysis science, fundamentally changing the way people understand and make decisions about geographical issues [5].

Entering the 21st century, geographic cartography is facing a new round of profound transformations and challenges. Firstly, multi-source data fusion has become a technological frontier. Remote sensing satellites, unmanned aerial vehicles, Internet of Things sensors, mobile terminals, and social media generate massive amounts of heterogeneous, multi-scale, and highly dynamic data. Effectively cleaning, integrating, and visualizing this data is the cornerstone of building an accurate and real-time digital world. Secondly, there is an urgent demand for full-space and three-dimensional visualization. Technologies such as real-scene 3D mapping, Building Information Modeling (BIM), and laser point clouds are driving cartography from 2D planar to 3D/4D stereoscopic and dynamic representations [6], aiming to construct a "digital twin" that synchronizes with the real world to meet complex applications such as smart cities, underground space management, and indoor navigation [7]. In addition, the deep integration of artificial intelligence is reshaping the cartographic process, from the automatic interpretation of remote sensing images to the intelligent generation of personalized maps, greatly enhancing efficiency and intelligence. The expression forms of maps are also increasingly tending towards dynamic interactivity and immersive experiences. Online interactive map services based on WebGL have become the norm [8], while virtual reality and augmented reality technologies immerse users in the map environment, providing unprecedented spatial cognitive experiences.

Throughout the grand journey of geographic cartography from primitive rock paintings to digital twins, its evolution clearly demonstrates a path from concrete depiction to abstract symbols, from empirical estimation to precise measurement, from static expression to dynamic analysis, and from expert tools to public services. Each technological breakthrough has profoundly expanded the boundaries of humanity's cognition and transformation of the world. Therefore, systematically reviewing its development trajectory and core principles is not only a matter of inheriting the long-standing cartographic civilization but also of crucial importance for promoting the continuous innovation of geographic information science in today's smart society and addressing future complex challenges.

2. The Principle System of Geographic Cartography

2.1. Principles of Projection Transformation

Projection transformation, serving as the mathematical foundation for converting the three-dimensional surface of the Earth into a two-dimensional planar map, is the core theory of geographic cartography. This principle primarily addresses the fundamental issue of how to scientifically project a spherical coordinate system onto a plane. During the Ming and Qing dynasties, Luo Hongxian's *Guangyu Tu* (Comprehensive Atlas of China) innovatively adopted a square grid positioning method. Although this method did not form a systematic modern projection theory, it effectively controlled the relative accuracy of distances and areas within local regions through a uniformly distributed square grid network, representing an initial attempt at equal-area projection [9]. The ingenuity of this method lies in its establishment of a

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unified planar rectangular coordinate system, providing a practical solution for the precise drawing of regional maps.

Modern cartography has since developed a complete theoretical system of projections, widely employing various projection methods such as the Mercator projection (equiangular cylindrical projection), Lambert projection (equal-area conic projection), and Albers projection. These projection techniques achieve precise control over spatial distortions through rigorous mathematical formulas [10]. Among them, the Mercator projection maintains constant azimuths, making it particularly suitable for maritime navigation. The Lambert projection ensures area accuracy and is commonly used in thematic maps requiring precise area calculations. For example, the 1:1,000,000 topographic maps of China adopt an equiangular conic projection. By setting two standard parallels within the projection zone, this method maintains directional accuracy while effectively controlling area deformation, achieving an optimized balance of projection errors. Such precise projection selection reflects the high level of mathematical maturity in modern cartography.

2.2. Scale and Precision Control

As a core parameter of map language, scale directly determines the information density and expressive precision of maps, serving as a bridge between the real world and map representation. During the Ming Dynasty, the *Daming Hunyi Tu* (Comprehensive Map of the Great Ming Empire), although not explicitly labeled with numerical scales, achieved systematic coverage of large-scale geographical spaces through precise tiling and stitching techniques, demonstrating ancient cartographers' profound understanding of scale relationships. By the Qing Dynasty, the *Qianlong Neifu Yutu* (Imperial Atlas of the Qianlong Period) explicitly marked a scale of 1:1,400,000 and incorporated the use of a square-mile grid (a precursor to the modern latitude-longitude grid), establishing a standardized spatial positioning system [11]. This combination not only provided a clear scale benchmark but also offered precise coordinate references, representing a significant advancement in precision control within traditional Chinese cartography.

Modern cartography has established a comprehensive hierarchical scale system (e.g., 1:5,000, 1:25,000, 1:100,000), with each scale level corresponding to specific data collection precision and content selection criteria. This systematic design enables the organization of geographic information in a pyramid structure, facilitating seamless multi-scale transitions from macro-regional planning to micro-urban management through digital zooming technology [12]. More importantly, modern geographic information systems (GIS) achieve an efficient workflow of "one-time data collection, multiple map productions" by establishing multi-scale databases, ensuring the coordination and consistency of geographic feature representation across different scales.

2.3. Symbol Systems and Information Encoding

As a key to the abstract representation of geographic information, the development of symbol systems reflects the evolution of cartography from artistic expression to scientific encoding [13]. The *Guangyu Tu* of the Ming Dynasty primarily employed pictorial representation techniques, using wavy lines to symbolize mountain ranges and squares to mark urban locations. Although intuitive, this concrete representation lacked quantitative standards. The *Huangyu Quanlan Tu* (Complete Atlas of the Imperial Realm) of the Qing Dynasty, incorporating Western surveying and mapping techniques, began to introduce standardized map symbols, including contour lines and legend systems [14], marking a significant shift toward scientific and standardized symbol systems in Chinese cartography.

Modern cartography adheres to the *Rules for Classification and Coding of Geographic Information*, establishing a complete classification system for map symbols. This system

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scientifically divides map symbols into three major categories: point symbols (e.g., settlements, isolated features), linear symbols (e.g., roads, rivers, boundary lines), and area symbols (e.g., water bodies, forests, administrative regions), and achieves multi-element coordinated representation through hierarchical coding [15]. Modern cartographic software such as ArcGIS supports dynamic symbol library calls and real-time rendering, allowing users to quickly switch display levels and symbol styles based on specific needs [16]. This intelligent symbol management system not only enhances cartographic efficiency but also ensures the consistency and professionalism of symbol representation, providing robust support for map visualization across diverse application scenarios.

2.4. Color Application and Visual Optimization

As a crucial means of enhancing map readability, the scientific progression of color application reflects the deep integration of cartography and visual perception theory. The *Daqing Wannian Yitong Dili Quantu* (Complete Geographic Map of the Eternal Unity of the Great Qing Empire) employed traditional green-and-blue landscape painting techniques, using contrasts in color brightness and saturation to distinguish administrative regions at different levels. Although lacking strict color standards, this artistic color application demonstrated early wisdom in visual hierarchy processing. Modern thematic maps, based on color psychology and visual perception principles, systematically employ color gradients (e.g., layered coloring of contour lines) and contrasting colors (e.g., red-cold to blue-warm sequences in heatmaps) to enhance information hierarchy and contrast [17].

Research indicates that the human visual system recognizes colors approximately three times more efficiently than text, prompting modern cartography to impose more scientifically rigorous requirements on color application. International standards such as ISO 2856 establish explicit technical specifications for color harmony, brightness contrast suitability, and color-blind friendliness in cartography [18]. Modern digital cartography also leverages color management technologies to ensure color consistency from screen display to printed output. Particularly in web maps, the establishment of color semantic association systems creates stable psychological mappings between specific colors and corresponding geographic concepts, significantly enhancing the efficiency of map information dissemination.

This comprehensive principles system-ranging from precise mathematical foundations to scientific visualization techniques-collectively forms the theoretical core of modern geographic cartography, ensuring that geographic information is perceived, understood, and utilized in the most effective manner possible.

3. Technological Evolution of Geographic Cartography

3.1. Prehistory to the Middle Ages: The Stage of Empirical Accumulation

The origins of geographic cartography are deeply rooted in humanity's early survival practices and spatial cognition. During prehistoric times, such as the Tswaane rock paintings dating back approximately 10,000 years, ancient peoples began using simple symbols to mark hunting routes and resource points, reflecting the most primitive map functions [19]. As civilizations developed, ancient Eastern and Western cultures formed distinct cartographic traditions. In China, the *Classic of Mountains and Seas* from the Warring States period primarily described mountains, rivers, and products in text but already contained systematic geographic concepts. In the West, the *Geography* written by the Greek scholar Ptolemy in the 2nd century AD proposed the revolutionary concept of latitude and longitude grids, laying a theoretical foundation for scientific cartography. The 4th-century Roman *Trojan Map* demonstrated early applications of scale [20]. During the Middle Ages, European T-O maps, though criticized for their circular Jerusalem-centered compositions and severely distorted geographic accuracy,

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visually embodied the cultural values dominated by religious worldviews at the time, marking a shift of cartography from purely geographic records to ideological tools [21].

3.2. Ming and Qing Dynasties: Technological Breakthroughs and Internationalization

The Ming and Qing dynasties represent a glorious period in Chinese and global cartographic history, marked by key technological breakthroughs and integration into the global perspective. In terms of surveying technology, Emperor Kangxi's *Complete Map of the Imperial Territory* (1708–1718) extensively employed triangulation and astronomical measurements to determine latitude and longitude, achieving an astonishing precision of 1:1,400,000 and surpassing European contemporaries by half a century in both conceptual and practical advancements. Regarding projection theories and cartographic rules, Luo Hongxian's *Guangyu Atlas* (1564) used a grid network for positioning, with principles approaching modern topographic map grids [22]. Meanwhile, Matteo Ricci's *Kunyu Wan Guo Quantu* (1602) introduced the Mercator projection, accurately presenting the polar regions and the global landscape for the first time in the Chinese-speaking world [23]. Additionally, significant innovations occurred in cartographic materials and printing techniques, evolving from Ming-era silk-based colored paintings to Qing-era copperplate bichromatic printing, which enhanced printing quality, map preservation, and dissemination efficiency.

3.3. Modern and Contemporary Eras: The Digital Revolution

Since the mid-20th century, geographic cartography has undergone a radical transformation driven by computer technology. The revolution began with the rise of computerized cartography, as manual digitization and scanning technologies in the 1950s enabled the first electronic conversion of map data [24]. The development of Canada's CGIS system in 1963 marked the birth of modern Geographic Information Systems (GIS), which linked map elements with attribute databases and initiated a new era of spatial analysis. Subsequently, the deep integration of remote sensing technology and GIS became a key driving force. After the launch of the Landsat satellite series in the 1970s, multi-source data fusion became feasible, while the popularization of professional software like ArcGIS and MapInfo enabled practical applications of complex spatial analysis and 3D modeling [25]. Entering the 21st century, cartographic technology has entered an intelligent development phase, with big data and artificial intelligence deeply integrated into the cartographic process. This integration has enabled automatic land-use classification, dynamic updates of real-time traffic maps, and personalized map customization based on web services, fundamentally reshaping map production modes and application scenarios.

4. The Historical Significance of Ming and Qing Cartographic Technologies

4.1. The Pinnacle of Traditional Cartographic Techniques

The Ming and Qing dynasties represent the zenith of traditional Chinese cartographic technologies, with their achievements primarily manifesting in three key areas. In terms of surveying precision, the Complete Map of the Imperial Territory achieved systematic application of triangulation and astronomical observations, successfully controlling longitude and latitude errors within ±0.5° [26]. This level of accuracy represented the technical limit achievable under contemporary conditions. Regarding cartographic standardization, Luo Hongxian's Guangyu Atlas established a unified symbolic representation system for geographic elements such as mountains, rivers, and cities, setting a standard paradigm for subsequent cartographic endeavors [27]. In terms of projection innovation, Matteo Ricci's Kunyu Wan Guo Quantu (Map of the Myriad Countries of the World) introduced polar-centered projections for the first time, breaking through the traditional "north-up" orientation and significantly

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expanding the Chinese worldview [28]. Collectively, these achievements constituted the most mature expression of traditional Chinese cartographic techniques.

4.2. A Bridge for East-West Technological Exchange

This period also served as a crucial conduit for technological exchange and integration between Eastern and Western cartographic traditions. Western missionaries, represented by Matteo Ricci, not only introduced advanced surveying methods such as triangulation and map projections but also disseminated China's grid-based positioning system and rich empirical surveying experiences to Europe, creating a bidirectional flow of knowledge. This profound technological dialogue found perfect expression in the Complete Map of the Imperial Territory, whose graticule system preserved China's traditional tiled assembly method while integrating Western mathematical foundations, creating a uniquely hybrid cartographic system [29]. Such exchanges not only propelled innovations in Chinese cartography but also injected fresh vitality into the global development of cartographic science.

4.3. Historical Limitations and the Need for Transformation

Nevertheless, beneath the glorious achievements of Ming and Qing cartographic technologies lay significant historical limitations. Data exclusivity manifested in the fact that map production primarily served imperial needs, lacking civilian participation and effective mechanisms for data updating. Technological development stagnated after the 18th century, failing to keep pace with Western innovations such as photogrammetry and topographic mapping standards [30]. Application scope remained confined to military and administrative domains for an extended period, without expanding into broader economic and social fields. These limitations ultimately subjected traditional Chinese cartography to profound transformational pressures when confronted with the onslaught of Western modern cartographic technologies.

5. Development Trends in Contemporary Geographic Cartography

5.1. Data Standardization and Sharing

Data standardization and sharing constitute the cornerstone of contemporary geographic cartography, with the core objective of establishing a unified "common language" for geographic information. The *Guidelines for Geographic Information Standardization*, led by the International Cartographic Association (ICA), along with national standards such as China's *Classification and Codes for Fundamental Geographic Information Data* (GB/T 13923) and *Geographic Information Metadata* (GB/T 19710), collectively form a multi-tiered, interconnected standardization system [31,32]. This system meticulously regulates the entire workflow, from underlying data formats (e.g., GeoJSON and GML for data exchange, GeoTIFF for raster data), metadata content (compliant with ISO 19115 series standards to ensure traceability of data sources, accuracy, and quality), to upper-level visualization expressions (e.g., Styled Layer Descriptor/Symbology Encoding standard SLD/SE for symbol library encoding).

Its profound significance lies in systematically dismantling the long-standing "information silos" that have persisted across different departments and institutions. For instance, in smart city construction, foundational topographic data from urban planning departments, real-time road network information from transportation authorities, and environmental monitoring point data from ecological agencies can now be integrated, analyzed, and visualized under a unified spatiotemporal framework. This integration supports comprehensive urban operational management and decision-making processes. Furthermore, the rise of national/regional spatial data infrastructures (e.g., the U.S. NSDI, Europe's INSPIRE) and open data platforms on a global scale is precisely built upon these standards, driving geographic information from closed professional domains toward open social applications and significantly unlocking data potential.

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5.2. Product Diversification and Customization

In terms of map product forms, contemporary geographic cartography is undergoing a profound transformation from single, static "paper maps" to diverse, dynamic "geographic information services," exhibiting unprecedented breadth and depth.

The proliferation of thematic maps stands as a notable hallmark of this trend. No longer confined to traditional topographic or administrative representations, these maps now deeply engage with various facets of social livelihood. For example, climate change maps generated from multi-temporal remote sensing data and meteorological observations visually reveal trends and impacts of global warming; population flow heatmaps created using mobile terminal location big data provide dynamic insights for urban planning, public health emergency response, and commercial site selection. Essentially, these maps represent customized solutions tailored to specific problems and user groups.

Dimensionally, maps are evolving from two-dimensional planar representations to three-dimensional spatial entities. By rapidly acquiring multi-angle, high-resolution imagery of ground features through oblique photogrammetry and integrating it with the detailed semantic information contained in Building Information Modeling (BIM), realistic 3D models with both authentic appearances and rich contextual information can be generated. These models not only serve as digital archives of urban landscapes but have also become indispensable analytical tools in urban planning and design, real estate management, smart security, and other fields.

More importantly, a fundamental transformation has occurred in map interaction modes. WebGIS-based interactive maps empower end-users with unprecedented autonomy. Users can freely overlay or hide different data layers according to their needs (e.g., transportation networks, commercial outlets, topographic relief), perform seamless zooming to access information at varying granularities, and instantly retrieve detailed attributes of ground features through click-to-query functions. This shifts maps from predefined, standardized "products" to customizable, interactive "services" [33], significantly enhancing the accessibility and practicality of geographic information.

5.3. Technological Convergence and Innovation

The deep integration and continuous innovation of cutting-edge technologies serve as the core engine driving contemporary geographic cartography, reshaping its technological paradigms and application boundaries. The integration of Artificial Intelligence (AI) with cartography has transitioned from exploratory stages to large-scale applications. Computer vision technologies based on deep learning, particularly advanced model architectures like YOLOv5 and U-Net, enable the automatic and precise extraction of ground features such as road contours, building boundaries, vehicles, and even tree species from high-resolution remote sensing imagery or point cloud data [34]. This achieves order-of-magnitude improvements in production efficiency and significantly enhances the timeliness of geographic information.

The introduction of blockchain technology brings innovations in trust and security to the field of geographic cartography. Its distributed, immutable, and traceable characteristics provide robust evidentiary support for the integrity of core map data (e.g., national boundaries, locations of critical infrastructure). In land management and real estate registration, the combination of blockchain and geographic information systems can construct a transparent, trustworthy platform for property rights registration and transactions, effectively preventing data tampering risks, simplifying confirmation processes, and enhancing the efficiency of social governance.

Augmented Reality (AR) technology has blurred the boundaries between digital maps and the physical world. By capturing real-world environments through smartphone or AR glasses cameras and utilizing Simultaneous Localization and Mapping (SLAM) technology for precise

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positioning, virtual geographic information can be seamlessly overlaid and registered onto real-world scenes within the user's field of view. This immersive spatial interaction mode [35] fundamentally transforms how we perceive and interact with our environment, creating entirely new application paradigms in navigation, on-site maintenance, cultural heritage preservation, and tourism experiences.

6. Conclusion

The development trajectory of geographic cartography represents a magnificent history of the evolution of human spatial cognition. From the rudimentary spatial markings on primitive rock art to the initial cartographic explorations of the world by ancient civilizations; from the pinnacle of traditional cartographic techniques embodied by the *Complete Map of the Imperial Territory* during the Ming and Qing dynasties to the digital revolution centered around Geographic Information Systems (GIS), each technological leap profoundly reflects a qualitative enhancement in humanity's ability to understand and transform the world. This progression clearly delineates an evolutionary path—from empirical perception to scientific cognition, from manual drafting to automated intelligence, and from static representation to dynamic analysis. During the Ming and Qing dynasties, large-scale field surveys and the fusion of Chinese and Western technologies established China's significant position in the history of global cartography. Meanwhile, the contemporary digital wave has completely overturned the traditional paradigms of cartography, transforming it from an art and science centered on "map-making" into an analytical and decision-making science centered on "geographic information." This transformation has not only expanded the connotations of cartography but also significantly broadened its application boundaries.

7. Discussion and Prospects

Looking ahead, the discipline of geographic cartography stands at a new historical crossroads. With the vigorous development of next-generation information technologies such as 5G/6G communication, the Internet of Things (IoT), and quantum computing, cartography will face more complex and profound challenges. Firstly, at the technological level, achieving precise representation and efficient processing of high-dimensional, dynamic, and realistic spatial data remains a core issue that urgently requires breakthroughs [36]. This necessitates not only the development of more advanced spatiotemporal data models and visualization engines but also the resolution of challenges related to the fusion and semantic understanding of massive, multi-source, heterogeneous data.

Secondly, at the methodological level, there is an urgent need to strengthen deeper interdisciplinary integration. Future development must transcend mere technological integration and move toward profound collaboration with cognitive science to scientifically elucidate the cognitive mechanisms underlying human interpretation of map information, thereby designing more intuitive interaction interfaces and visualization schemes. Collaboration with computer vision and artificial intelligence will drive the transition from "automatic cartography" to "autonomous cognition," enabling map systems to proactively discover spatial patterns and predict spatiotemporal phenomena [37]. Integration with social sciences will deepen our understanding of the role of maps in social governance and cultural construction, ensuring that technological advancements serve human well-being.

Finally, at the application and ethical levels, future geographic cartography will place greater emphasis on human-machine collaboration and contextual adaptation. Maps will no longer be uniform, static products but personalized intelligent agents capable of understanding user intentions, adapting to specific contexts, and evolving dynamically over time. Meanwhile, as cartographic capabilities reach unprecedented levels, ethical considerations such as data

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security, privacy protection, and avoiding the entrenchment of real-world biases in algorithms [38] must become integral to the discipline's development. The future evolution of geographic cartography will undoubtedly be a comprehensive innovation process grounded in data-driven approaches, centered on intelligent computing, characterized by interdisciplinary fusion, and fundamentally aimed at serving human society. Only by keeping pace with technological trends, deepening theoretical innovation, and strengthening interdisciplinary collaboration can we successfully construct a next-generation spatial cognition system that is more precise, intelligent, and inclusive [39], continuing to play an indispensable role in the era of digital civilization.

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